July 2000 Progress Report for ER62341

1. **Principal Investigator:** Patrick Minnis, NASA Langley Research Center, Hampton, VA

   Co-Investigators: David F. Young, NASA Langley Research Center, Hampton, VA
   Bing Lin, NASA Langley Research Center, Hampton, VA
   David P. Duda, Hampton University, Hampton, VA
   Xiquan Dong, University of Utah, Salt Lake City, UT

2. **Title:** Development of Improved Techniques for Satellite Remote Sensing of Clouds and Radiation Using ARM Data

3. Scientific Goals

One of the primary goals of this research is to improve the characterization of clear-sky radiances used for cloud detection and cloud property retrievals. This goal will be accomplished by examining the angular, temporal, and humidity dependence of surface emissivity and reflectance at various wavelengths; the relationships between observed surface-skin, model-predicted, and air temperatures; and the relationship between skin temperature and cloud cover. New bidirectional reflectance distribution functions (BRDF) will be developed and tested for a variety of surfaces and wavelengths. Another objective is the validation of satellite-derived cloud and surface properties and broadband fluxes using ARM surface and aircraft datasets as well as other satellite data. This validation will include the set up and testing of semi-operational code and comparison of its output with corresponding ARM data. Improved cloud algorithms are the focus of many aspects of this research including the detection and interpretation of overlapping clouds from satellite data; discrimination of clouds over snow and determination of their optical properties; explicit determination of partial cloud cover in standard imager pixels, estimation of cloud particle shape; determination of drizzling areas; and better estimates of cloud thickness. Our other objectives are to collaborate with other ARM investigators to study phenomena observed during field programs including the ARM IOPs and Nauru99 and to further develop new uses for ARM datasets.

4. Accomplishment Outline

- Tested range of BRDFs derived from MPIR and helicopter measurements over SGP using dual satellite measurements.
- Found further evidence of very significant azimuthal anisotropy in land surface longwave emissions using dual satellite, helicopter, and ARESE-I ER-2 data.
- Improved nighttime cloud property retrievals for low clouds by incorporating a new inversion-cloud emittance parameterization.
- Completed and implemented semi-operational code for multispectral nighttime and daytime retrieval during ARESE-II.
- Performed first validations and tests of new cloud retrieval code using ARM SGP surface instruments.
- Found that land and snow surface temperatures are extremely sensitive to cloud cover during all times of day from combined cloud and IR radiometer datasets.
- Determined that cloud plumes deriving from the island dominate the cloud cover over Nauru and compromise the representativeness of the site for the tropical marine environment.
- Compared NSA surface observer and satellite cloud amounts for cloud validation.
- Supported both ARESE-II and Spring SGP cloud IOP with satellite data, products, and predictions.
- Revised and received acceptance of 3 journal articles on Arctic clouds; revised and published 5 other journal articles on ARM topics; submitted paper and 5 extended abstracts on ARM results.

5. Accomplishments and Progress Summary

A. Surface properties

A set of four BRDF models were tested using matched GOES-8, GOES-10, TRMM VIRS, NOAA-12 and 14 AVHRR visible channel datasets over the ARM SGP domain. Two of the models (GOES and ERBE) are currently used in operational ARM and CERES cloud retrievals and radiative flux inversions, while two new ones (MPIR and CERES) were derived from ARM-UAV MPIR and CERES-ARM Radiation Experiment (CARE) helicopter data taken over the areas surrounding the SGP central facilities. The comparisons of the narrowband visible albedos derived from dual, collocated satellite measurements indicated that the ERBE and GOES models, in general, produced the smallest bias and random errors, while the CERES and MPIR models produced the most significant errors in albedo. Although the latter pair were derived directly from central Oklahoma data, they were not as representative as the other models because the atmospheric corrections were inadequate or the angular sampling was insufficient. The comparisons and helicopter measurements indicated that some asymmetric diurnal variations of spectral reflectance occurred for some areas, however, the results are not conclusive. All of the models, except CARE, produced acceptable errors in albedos for low solar zenith angles (NOAA-14 AVHRR). The RMS errors ranged from 22 to 35% for high solar zenith angles (NOAA-12). Differences in the filter functions of the various visible channels also contributed to the differences in albedos after correction with the BRDFs. Surface microwave emissivities in the SGP area were found to vary substantially with soil moisture and time of day, perhaps due to the effects of dew. These effects are still being examined.

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Lin, B. and P. Minnis, 2000: Variations of land surface microwave emissivities over the ARM Southern Great Plains site. Presented at the *Tenth ARM Science Team Meeting*, San Antonio, TX, March 13-17.

B. New semi-operational cloud code

Updated multispectral cloud retrieval algorithms, the Visible Infrared Solar-infrared Split-window Technique (VISST) and the Solar-infrared Infrared Split Window Technique (SIST), were implemented to operate in near-real time using GOES-8 data. A new 5-segment correlated-*k* distribution method was used to correct all of the infrared channel temperatures for atmospheric attenuation; a new set of 3.7-µm cloud reflectances was derived using a combination of 5 solar-constant and filter-function weighted reflectance models computed for spectral subintervals in the solar-infrared band; and a new non-linear interpolation technique was implemented to improve reflectance estimates between nodal points. A new parameterization of cloud brightness temperatures was included to enable the retrieval of properties for clouds with temperatures greater than or equal to upwelling background temperature. Revised calibrations of the visible channel results in greater optical depths than previously estimated. This new method uses Rapid Update Cycle (RUC) prognostications of temperature and humidity in near-real time mode and can use other, more accurate temperature fields in delayed or reprocessed analyses. In addition to cloud temperature, height, optical depth, broadband shortwave albedo and longwave flux, the programs produce cloud phase, effective droplet radius *r*, effective ice crystal diameter *D*, and liquid and ice water paths, LWP and IWP, respectively. Figure 1 shows examples of the new products with a visible-channel image. Some of the larger water droplet sizes are due to overlapping ice clouds. Work continues on the algorithm to improve cloud detection and interpretation near the terminator hours and to better discriminate clouds from snow over the SGP.

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C. Validation of cloud properties

Because of the relatively frequent occurrence of stratus during the Spring 2000 Cloud IOP at the SGP, we were able to compare surface radar-radiometer retrievals with those from GOES-8 for 7 days as summarized in Table 1. The GOES-8 derived values of r, τ, and *LWP* differ from the corresponding surface-based results by 0.9 μm, -0.8, and 14 gm^{-2}, respectively. The respective relative differences are 10%, 2%, and 6%. Additional comparisons were performed using retrievals of *r* based on 3.7 and 1.6-µm radiances taken over the SGP site by the VIRS imager on the TRMM satellite and the ATSR instrument on the ERS-2 orbiter. The 1.6-µm channel is available on the MODIS and will eventually be part of the AVHRR and GOES images. The 1.6-µm-derived droplet radii were generally smaller than their 3.7-µm counterparts. The mean difference of 0.9 µm is consistent with the occurrence of larger droplets at the top of the cloud. Thus, differences in Table 1 may be entirely due to the vertical structure of the clouds. A similar comparison of cirrus-cloud particle sizes showed that the 1.6-µm retrieval yields larger ice crystal sizes than the 3.7-µm retrieval because the larger sizes are near the bottom of the cloud. The vertical structure of the cloud particle sizes affects the spectral retrievals differently because the signal most affecting the 3.7-µm radiance is from the top of the cloud. The 1.6-µm radiances are reflected by particles that are deeper within the cloud. While these initial results are extremely encouraging, they represent only a small portion of the cloud conditions that need to be validated with the ARM datasets. Furthermore, in situ data must be used to validate the surface-based retrievals.

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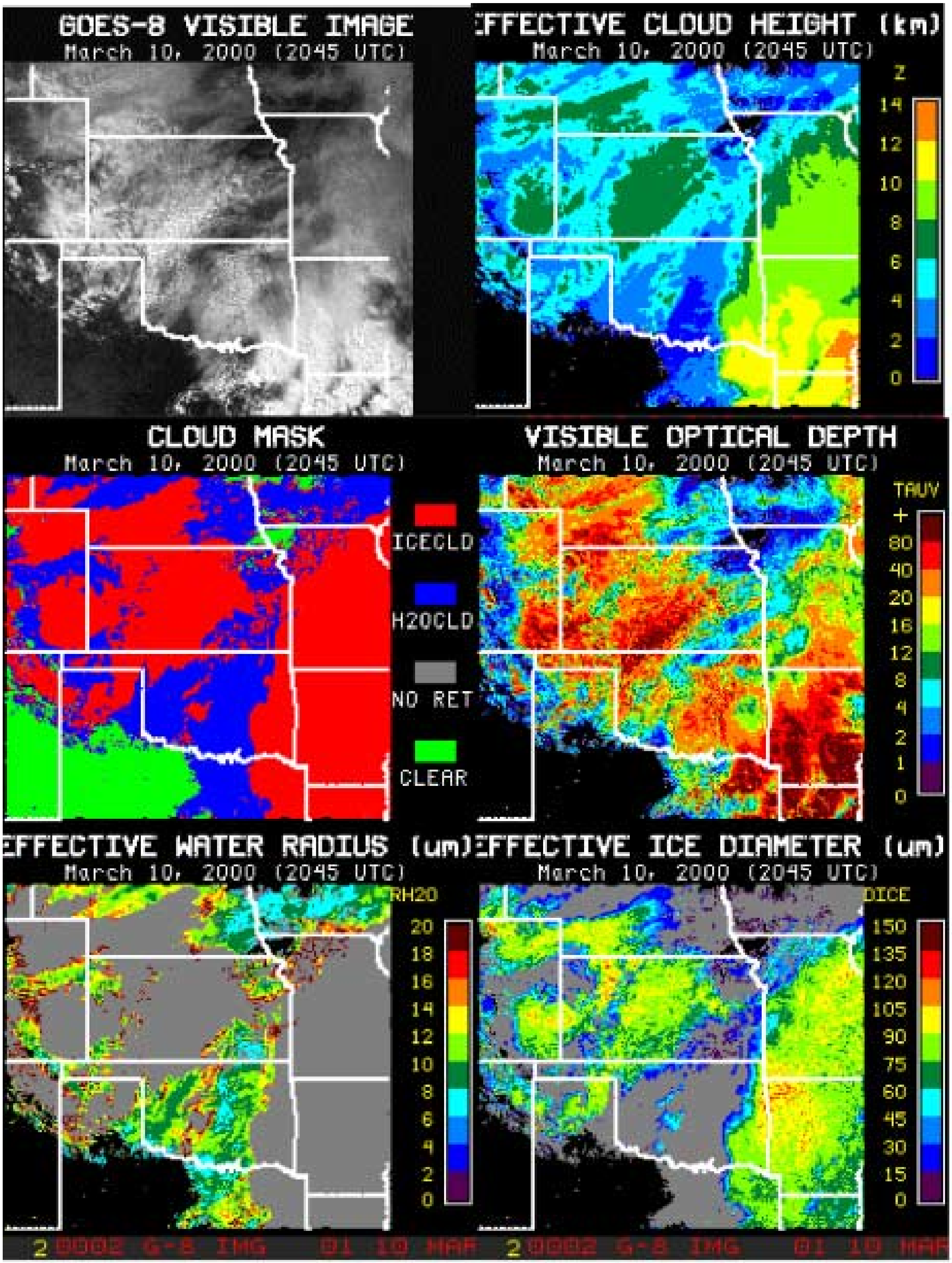

Figure 1. Example of new near-real time cloud products derived from GOES-8.

Table 1. Comparison of cloud properties derived over the ARM SGP from GOES-8 (G8) and from the ARM CART instruments (sfc) during ARESE-II and the Spring 2000 Cloud IOP.

Day in March	1st hr UTC	Last hr UTC	τ_{G8}	r_{G8} µm	LWP_{G8} gm^{-2}	τ_{sfc}	r_{sfc} µm	LWP_{sfc} gm^{-2}
3	17.50	21.50	24.46	8.41	130.90	38.1	6.9	166
14	15.50	21.50	33.03	9.71	215.00	29.1	10.1	181
15	14.50	17.50	32.88	12.55	268.92	27.6	7.9	148
17	17.50	20.50	56.00	11.28	394.87	59.9	10.6	412
19	14.00	17.50	21.56	10.01	125.99	24.1	6.5	100
21	16.00	21.00	55.30	9.82	367.48	46.5	10.2	325
29	16.00	23.00	48.14	10.17	312.85	54.9	10.2	365

D. Skin surface temperature sensitivity

As a first step towards improving estimates of surface temperature in cloudy conditions, we examined the relationship between skin temperature and cloud shadowing at the ARM SGP central facility under overcast and partly cloudy skies. Surface skin temperature was measured by the down-looking wide field-of-view infrared (9.6 – 11.5 µm) pyrometer, while the up-looking SIRS or BSRN pyranometers measured the total downward shortwave (0.2 – 5 µm) hemispheric irradiance. Skin temperatures derived from 1-min averages of the IR data were compared to the air temperatures measured at a height of 2 m. Under overcast conditions at night, the 2 m air and skin temperatures were within 1 K of each other. In daytime under both overcast and mostly cloudy conditions, the air/skin temperature differences correlated well with the downward shortwave hemispheric irradiance (Figure 2) suggesting that skin temperature can be accurately estimated from surface air temperature during cloudy conditions. Methods to derive downward solar flux from satellite could be used with surface air temperature measurements to determine the skin temperature. Partly cloudy conditions are more complex. A comparison of the skin temperature and shortwave irradiance under skies with scattered cumulus showed that the skin temperature at SGP reacts rapidly to changes in solar insolation. The lag between the shortwave irradiance and skin/air temperature differences is less than ÿ min. Under such conditions, skin temperature can fluctuate as much as 10 K in 3 min. Using ARESE GOES imagery, it was found that at night, the skin temperatures in clear regions were substantially less than those underneath adjacent areas with low cloud cover. The local air temperature provided a good estimate of the cloudy-sky surface skin temperature.

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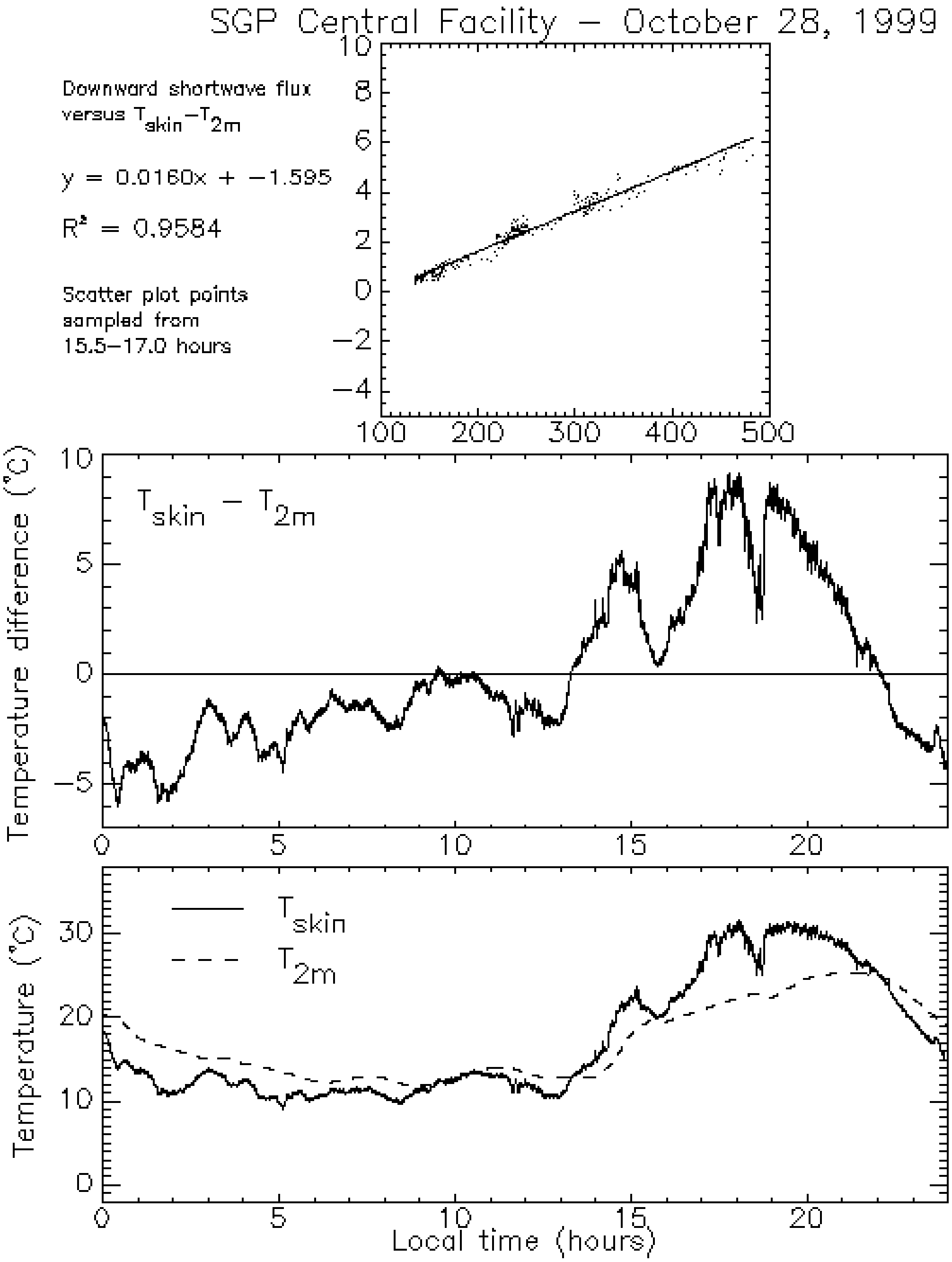

Figure 2. Plot of the air/skin temperature difference as a function of downward solar irradiance at the Southern Great Plains (SGP) Central Facility on October 28, 1999. Time series of the 2-m air temperature, the measured IR skin temperature and the air/skin temperature difference measured at the SGP Central Facility on October 28, 1999.

E. NSA cloud cover and radiative forcing

Cloud amounts, heights, and temperatures were derived for domains centered on the NSA (Barrow) and SHEBA ship sites for the FIRE ACE period during 1998. The results from SHEBA are documented in three papers that were revised and have been accepted for publication in *JGR*. Those studies used surface and aircraft measurements to validate the satellite retrievals. The ARM NSA site is more challenging for satellite retrievals because of the sharp gradients in surface albedo and temperature due to the confluence of sea ice, open water, and land surfaces including high, rugged mountains. The results for the NSA domain summarized in Figure 3 show significant east-west gradients in cloud fraction and altitude for nearly the entire FIRE-ACE period. The cloudiness was dominated by low clouds (< 3 km) around Barrow. These

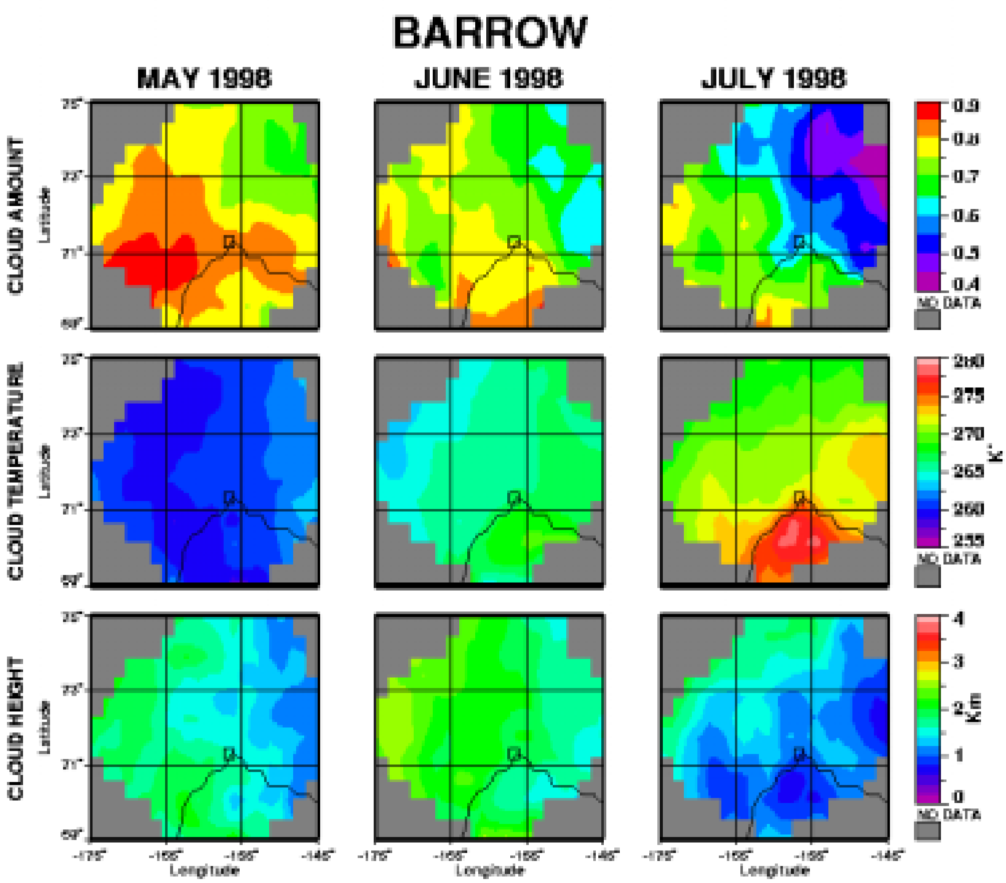

Figure 3. Mean cloud parameters over the NSA domain derived from NOAA-12 and -14 AVHRR data during the FIRE-ACE/SHEBA period.

initial analyses serve as a prototype for more routine satellite retrievals over the ARM NSA domain. The cloud fractions were compared to the available surface observer reports of cloudiness. The surface observations were rather crude being provided in values of 0/8, 3/8, 5/8, and 8/8. Direct comparisons were effected by binning the satellite results into four similar categories. The results in Table 2 show that 67% of the matched measurements were in the same category while only 8% differed by more than 1 category. Much of the difference may be due to the scale differences. The satellite values represent the mean for an area within 25 km of the NSA site, while the surface observations may represent only a fraction of that area because of foreshortening by the low-level clouds. Cloud forcing was also computed for this period and will be compared to the surface-derived values. A more detailed study is under way to compare lidar-ceilometer cloud amounts with smaller area averages of satellite pixels. Data taken later will be compared with the NSA radar results. Algorithms for deriving cloud and radiation properties for other seasons are being developed.

Table 2. Comparison of surface and satellite-derived cloud amounts over ARM NSA, May-July 2000. AVHRR values are based on data within a 25-km radius; surface observations are in 0/8, 3/8, 5/8, and 8/8.

AVHRR	Barrow Observer Ac (%)			
Ac (%)	0 –15	15 – 50	50 – 85	85 - 100
0 –15	10	34	4	9
15 – 50	0	21	12	15
50 – 85	0	14	15	26
85 – 100	2	6	43	242

References

Minnis, P., D. R. Doelling, V. Chakrapani, D. A. Spangenberg, A. Mahesh, S. K. Pope, and F. P. J. Valero, 2000: AVHRR-Derived Cloud Radiative Forcing Over the ARM NSA and SHEBA Site During FIRE ACE. Presented at the *Tenth ARM Science Team Meeting*, San Antonio, TX, March 13-17.

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F. Nauru cloud cover

Nauru99 was an IOP dedicated to investigating the way measurements on the island of Nauru represented those in the surrounding ocean. Data from two research vessels, the TAO buoy array and the ARCS-2 station on the island were compared. The meteorological satellite GMS-5 produces hourly images from the test area at a resolution of 1.25 km in the visible spectrum and 5 km in the infrared. These images were analyzed to investigate cloud properties on a large scale, and to examine the relationship between cloud conditions in the region surrounding Nauru compared to those in the ocean region.

Figure 4 shows a typical image collected over Nauru at approximately 1630 LT, June 29, 1999. The positions of Nauru and the two research vessels are shown in the image. The gridded total cloud amount (on a 0.5 degree grid) is overlaid on the image. As can be seen from this image, the cloud amount estimates correspond well with the visual appearance of cloud. When the cloud amount estimates were averaged over an entire month, the results shown in Figure 5 were obtained. These figures show the amounts of total, low, mid, and high level cloud cover. The low, mid, and high cloud amounts were summed to provide the average total cloud amount for the period June 16-July 16, 1999. The average total cloud amount is less than 50%, in reasonable agreement with measurements from surface sites. High cloud is the greatest contributor to this total cloud amount.

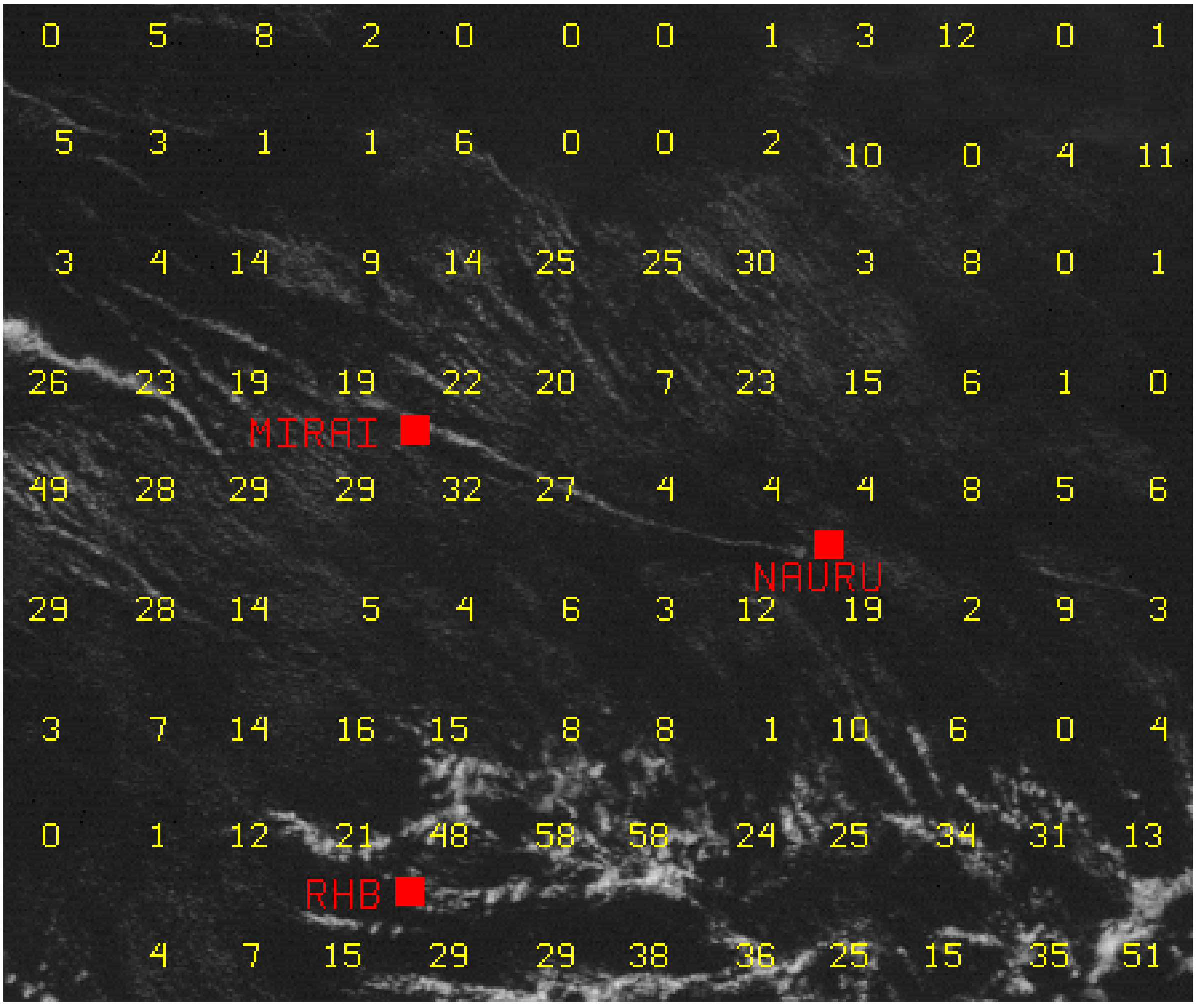


Figure 4. Cloud fractions for 0.5° regions over the Nauru99 domain from GMS imagery taken at 0330 UTC, June 29, 1999.

One significant item in Figure 4 is a cloud plume, measuring over 100 km in length, originating at the island and passing almost directly overhead the Mirai. The characteristics of the cloud plume originating over the island were determined by analyzing the high-resolution GMS visible data for an entire year. It is difficult to detect in the 5-km imagery. This plume originates over Nauru Island, presumably as the result of surface heating during the day. Advection carries the plume clouds to the northwest. Because the ARM surface site is located on the leeward side of the island, the measurements may be biased by the plume, which is not particularly typical of the surrounding ocean despite the appearance of cloud streets in Figure 4.

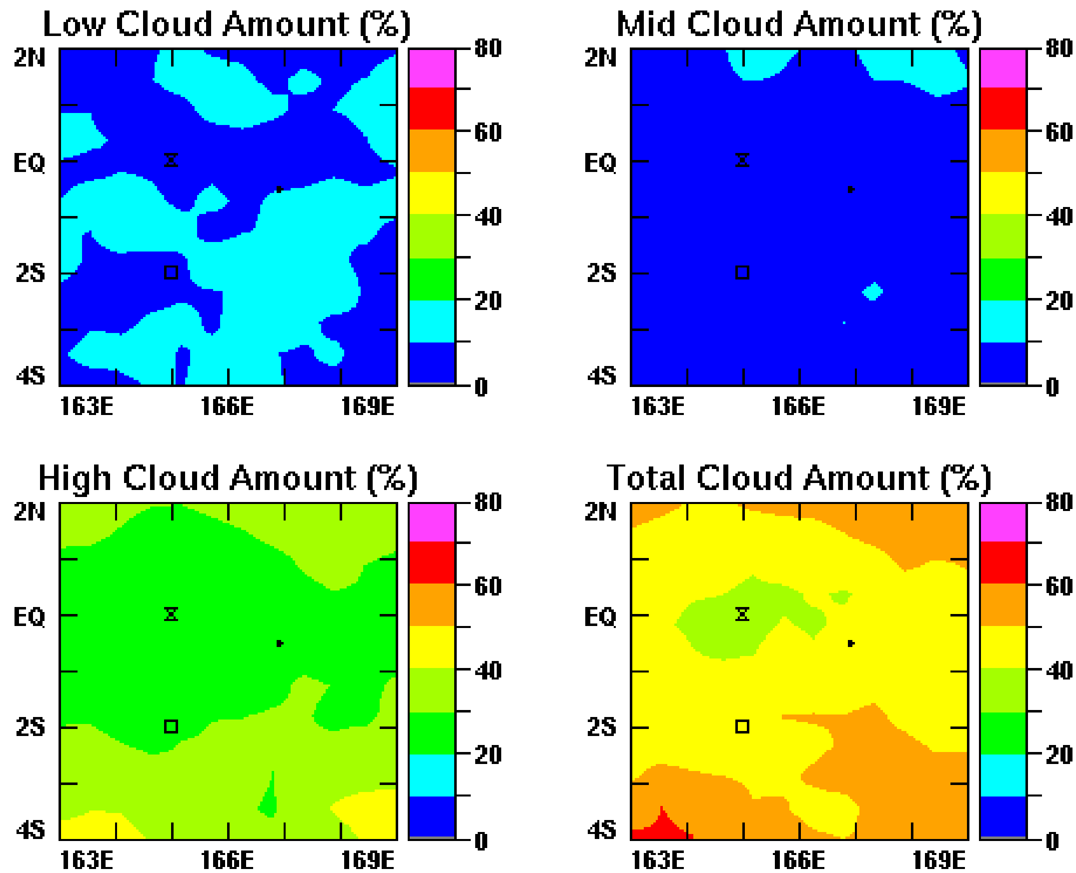
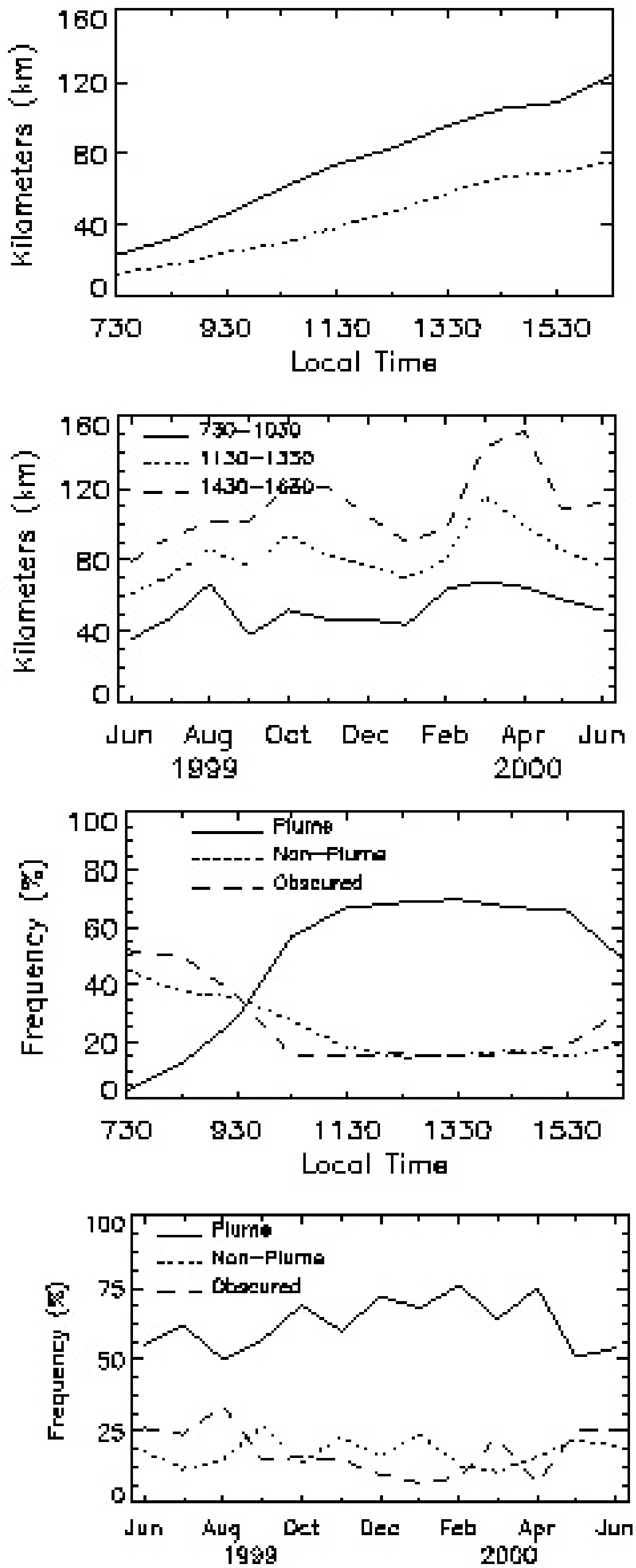


Figure 5. Mean cloud amounts derived from GMS-5 data during Nauru99, June 16 – July 16, 1999. The “x” and box refer to the locations of the R/V Mirai and Ron Brown, respectively.

To determine if this island-driven cloud cover is a significant feature, the GMS data taken between June 1999 and June 2000 were examined in detail for plume occurrence. Figure 6 summarizes some of the findings. The average plume begins developing around sunrise and rapidly grows to a length exceeding 120 km on average (Fig. 6a). The maximum length is 425 km. The plume diurnal variation is strong in all seasons (Fig. 6b) with mean length variations occurring only during the morning. During the afternoon, the cloud plume is observable almost 65% of the time in all seasons (Figs. 6c and d). It is obscured or absent



a) Mean plume length as function of local time, June 1999 - June 2000.

b) Monthly mean cloud plume length for different local times.

c) Mean daytime variation of cloud plume, non-plume, and obscured condtions, June 1999 - June 2000.

d) Monthly mean plume, non-plume, and obscured conditions between 1030 and 1630 LT.

Figure 6. Mean plume characteristics derived from GMS-5 visible data over Nauru Island.

between 35% during the afternoon and up to 95% during the early morning. Unlike the cloud streets seen in Figure 4, the plume follows the wind direction at 850 hPa indicating that the plume is the result of advection of the clouds or convective instability formed over the island. The cloud streets appear to form at a 30° - 45° angle to the prevailing wind direction. Preliminary analyses of the cloud plumes using 1-km AVHRR data suggest that the average effective droplet size is larger than that found within the surrounding cloud streets. An irregular pattern of large and small effective droplet radii suggest the occurrence of drizzle in some of clouds. Visual observations from aircraft during Nauru99 confirm that some of the plume clouds were drizzling. This island-anchored cloudiness does not appear to be typical of the surrounding marine environment although similar plumes have been observed emanating form other TWP islands. If the ARM surface instruments view this plume much of the time, then it is likely that those measurements may not be very representative of the surrounding environment and may need to be moved. Studies of the island representativeness are continuing. High-resolution AVHRR data will continue to be analyzed for cloud microphysical properties and for detection of the plume at night. Comparisons between ship, island, and satellite data will also be performed including both cloud and radiation properties.

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6. Attached figures

Att. Fig. 1. Plot of the air/skin temperature difference as a function of downward solar irradiance at the Southern Great Plains (SGP) Central Facility on October 28, 1999. Time series of the 2-meter air temperature, the measured IR skin temperature and the air/skin temperature difference measured at the SGP Central Facility on October 28, 1999. Demonstrates the rapid response of the skin temperature to cloud shadows, an effect that impacts cloud property retrievals from satellite.

Att. Fig. 2. Example of new near-real time cloud products derived from multispectral GOES-8 data. Some of these products were validated using both surface and airborne ARM measurements in and around the SGP Central Facility. They will be used to improve large- and meso-scale models.

Att. Fig. 3. Monthly mean cloud properties derived from AVHRR data over the ARM NSA domain. A prototype Arctic algorithm was developed and applied to data taken during the FIRE-ACE?SHEBA IOP. These results and the initial algorithm will serve as the basis for the development of an operational ARM Arctic algorithm.

Att. Fig. 4. Example of a cloud plume emanating from Nauru Island during the Nauru99 IOP. The plume is frequent presence in the ARCS-2 domain and may impact the measurements made from the island.

Att. Fig. 5. Statistics describing the Nauru cloud plume. It is a diurnal phenomenon occurring during all seasons. The plume has been measured at a length of 425 km and covers part of the leeward side of the island.

7. Current grant refereed publications

Curry, J. A.; Hobbs, P.; King, M. D.; Randall, D. A.; Minnis, P.; Uttal, T.; Isaac, G. A.; Pinto, J. O. et al.: FIRE Arctic Clouds Experiment. *Bulletin of the American Meteorological Society*, **81**, 5-29, 2000.

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8. Current grant extended abstracts

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9. Update of papers in previous report

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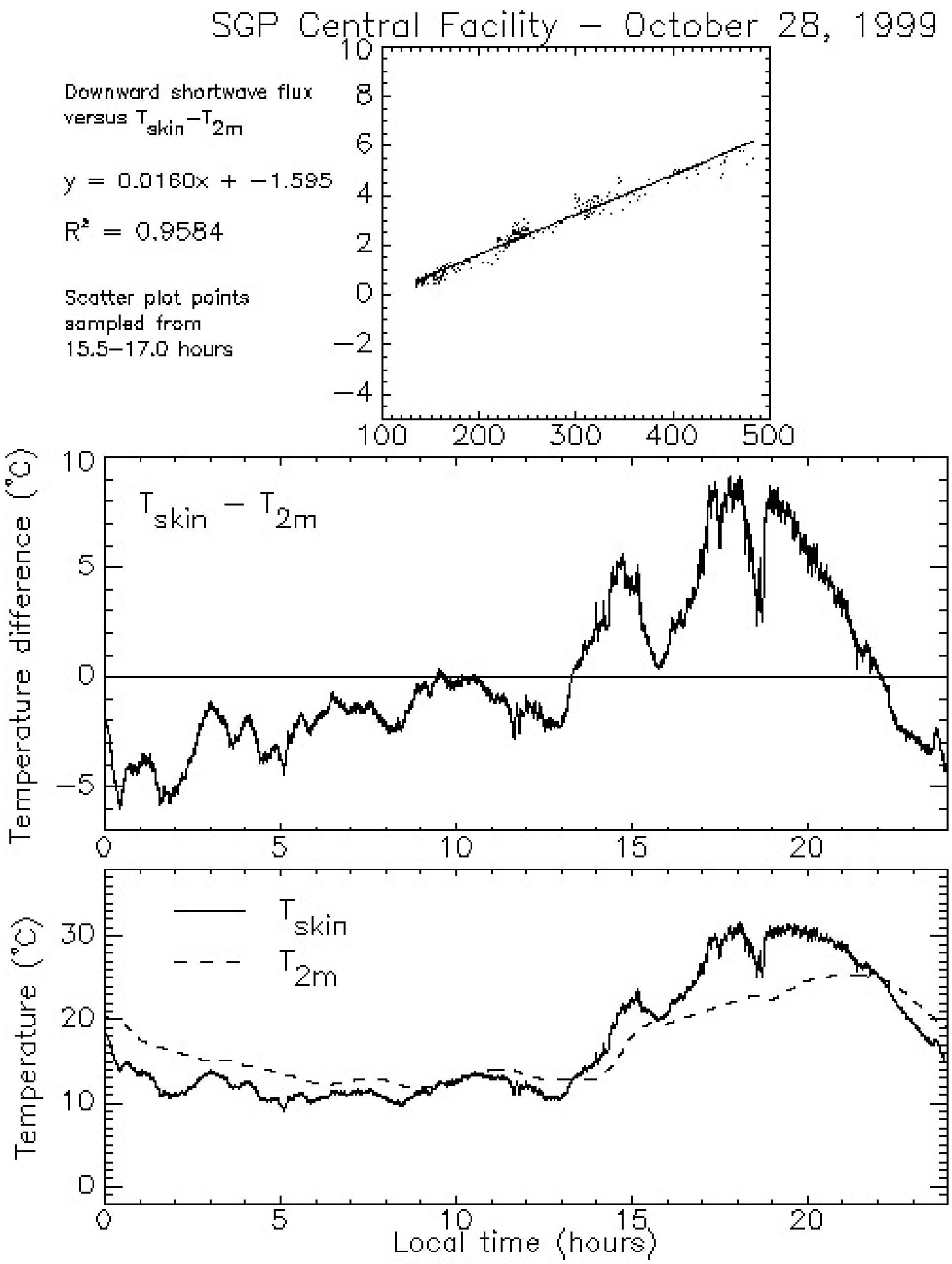
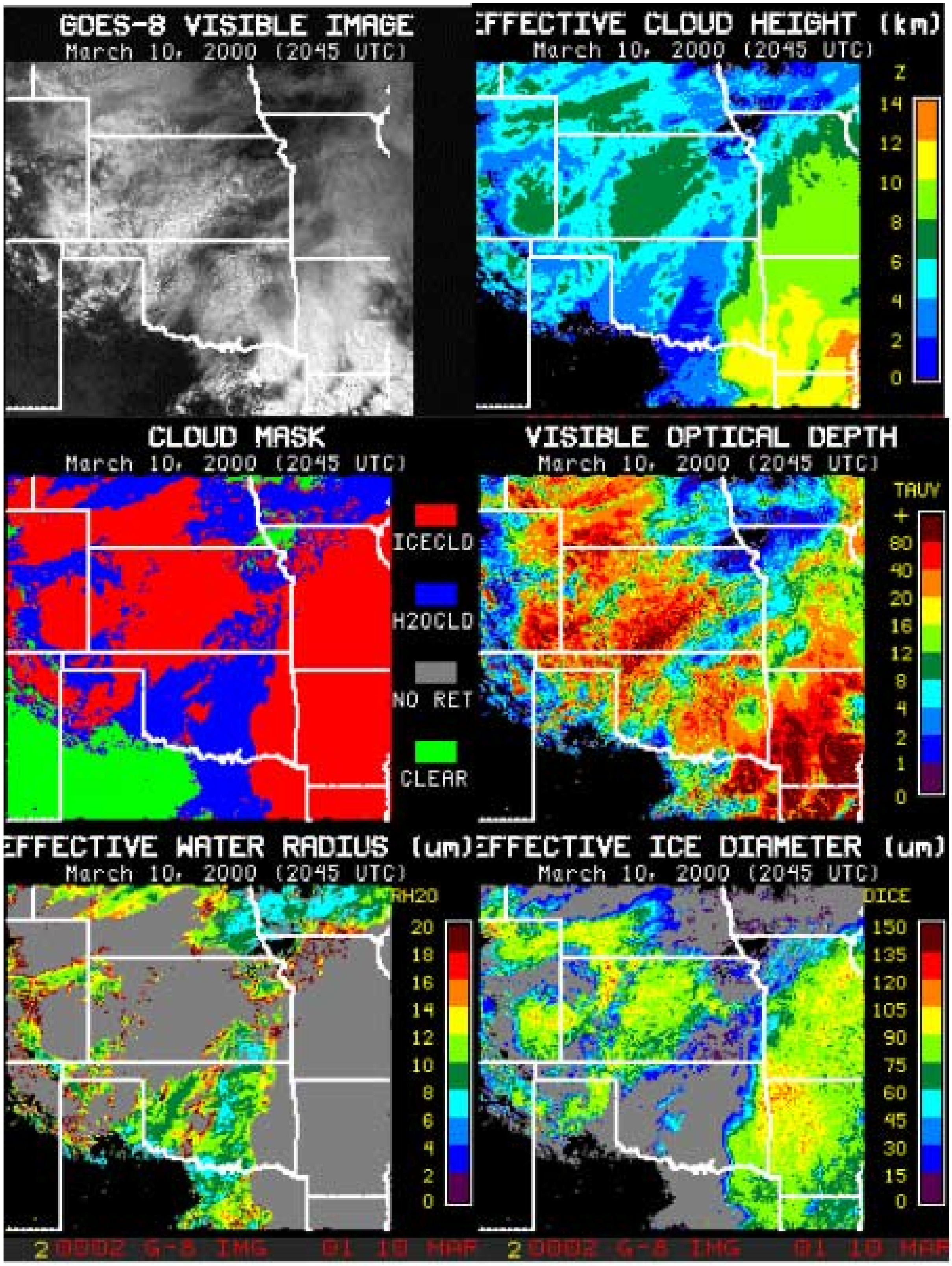
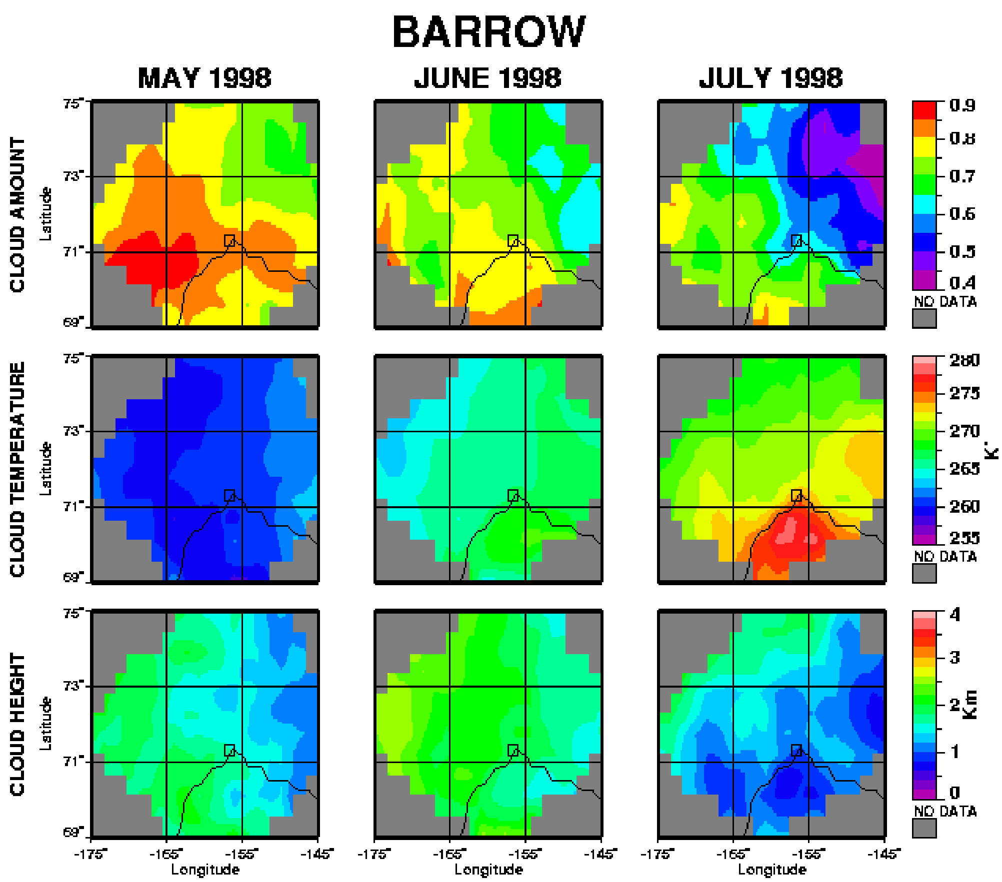


SGP Central Facility – October 28, 1999
Downward shortwave flux
versus $T_{skin}-T_{2m}$
y = 0.0160x + –1.595
R^2 = 0.9584
Scatter plot points
sampled from
15.5–17.0 hours
$T_{skin} - T_{2m}$
Temperature difference (°C)
T_{skin}
T_{2m}
Temperature (°C)
Local time (hours)

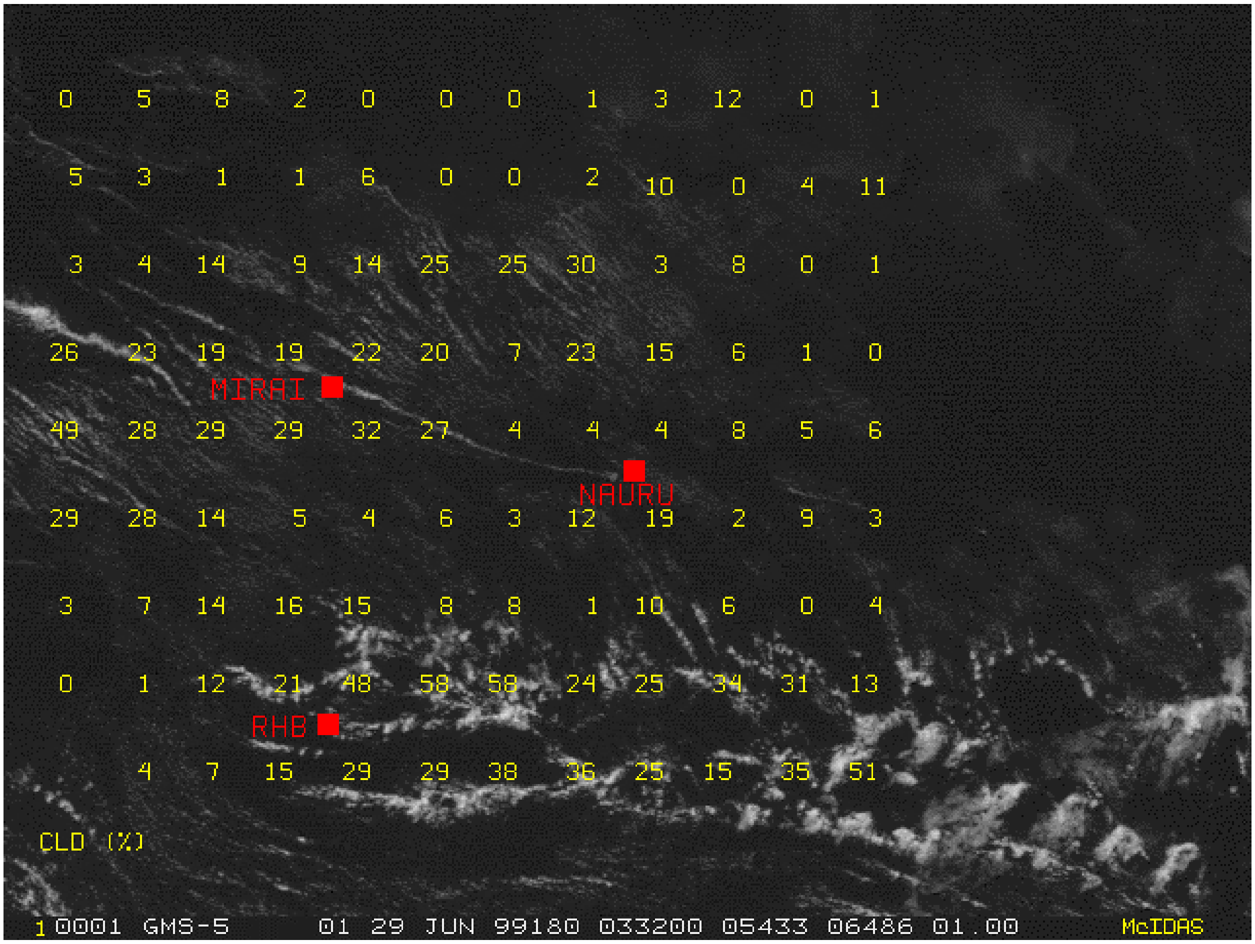
Att. Fig. 1.


GOES-8 VISIBLE IMAGE
March 10, 2000 (2045 UTC)
EFFECTIVE CLOUD HEIGHT (km)
March 10, 2000 (2045 UTC)
Z
14
12
10
8
6
4
2
0
CLOUD MASK
March 10, 2000 (2045 UTC)
ICECLD
H2OCLD
NO RET
CLEAR
VISIBLE OPTICAL DEPTH
March 10, 2000 (2045 UTC)
TAUV
+
80
40
20
16
12
8
4
2
1
0
EFFECTIVE WATER RADIUS (um)
March 10, 2000 (2045 UTC)
RH2O
20
18
16
14
12
10
8
6
4
2
0
EFFECTIVE ICE DIAMETER (um)
March 10, 2000 (2045 UTC)
DICE
150
135
120
105
90
75
60
45
30
15
0

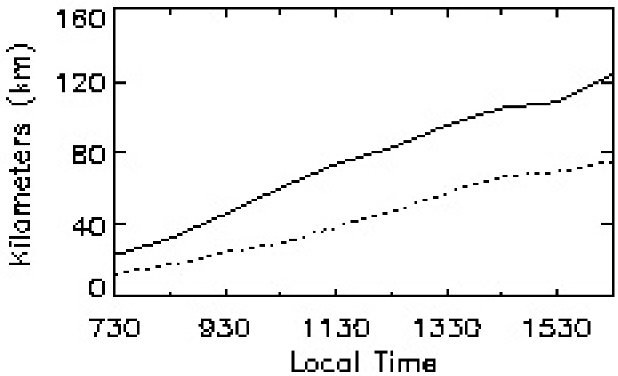
Att. Fig. 2.


BARROW
MAY 1998
JUNE 1998
JULY 1998
CLOUD AMOUNT
CLOUD TEMPERATURE
CLOUD HEIGHT
Latitude
Longitude
75°
73°
71°
69°
-175°
-165°
-155°
-145°
0.9
0.8
0.7
0.6
0.5
0.4
NO DATA
280
275
270
265
260
255
K°
4
3
2
1
0
Km

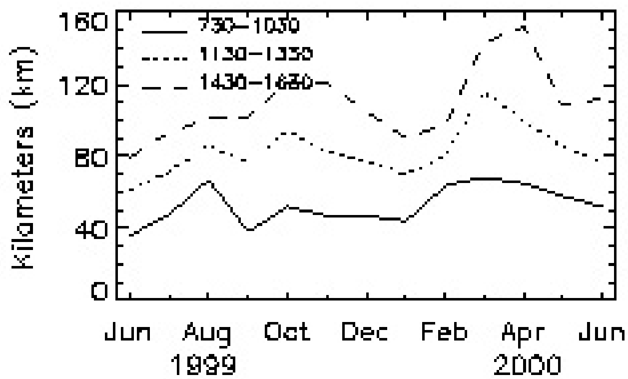
Att. Fig. 3.


MIRAI
NAURU
RHB
CLD (%)
1 0001 GMS-5 01 29 JUN 99180 033200 05433 06486 01.00
McIDAS

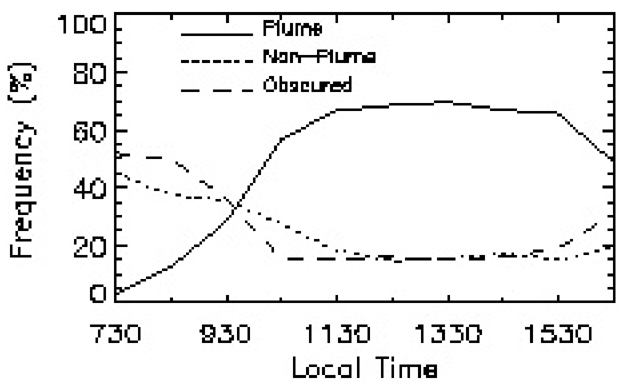
Att. Fig. 4.



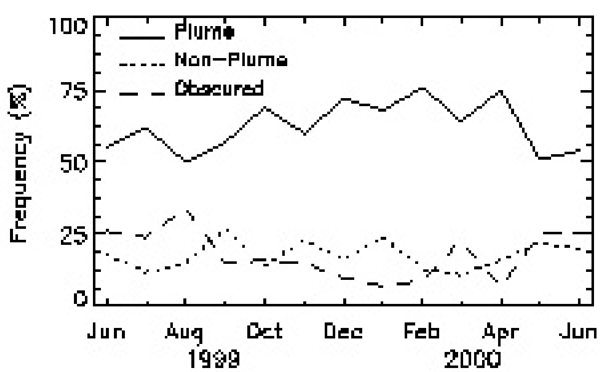
a) Mean plume length as function of local time, June 1999 - June 2000.



b) Monthly mean cloud plume length for different local times.



c) Mean daytime variation of cloud plume, non-plume, and obscured condtions, June 1999 - June 2000.



d) Monthly mean plume, non-plume, and obscured conditions between 1030 and 1630 LT.

Att. Fig. 5